

Photon Counting Detectors for the 1.0 - 2.0 Micron Wavelength Range

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Abstract - We describe results on the development of > 200 μm diameter, single-element photon-counting detectors for the 1-2 micron wavelength range. The technical goals include quantum efficiency in the range 10 - 70%; detector diameter > 200 μm ; dark count rate below 100 kilo counts-per-second (cps), and maximum count rate above 10 Mcps.

I. INTRODUCTION

Single photon counting systems operating in the 1.0 - 2.0 micron wavelength range are of interest for many applications. For active remote sensing optical instruments, operating at eye-safe wavelengths greater than 1.4 μm (i.e. beyond the retinal hazard region) allow high-optical-power eye-safe laser transmitters. Approaches for achieving efficient photon counting at these wavelengths include: InGaAs APDs in Geiger mode, InGaAs alloy photomultiplier tubes and others. Table I gives a summary of several of the efforts to date.

Table I. PHOTON COUNTING DETECTORS
FOR > 1.0 MICRON WAVELENGTH.

	InGaAs APD Epitaxx EPM239 AA[1]	InGaAs APD Array [2]	PMT Hamam atsu R- 5509-43 [3]	Hybrid PMT Intevac [4, 5]
Quantum Eff. @ 1.06 μm	0.08	0.50	0.0048	0.10
Max. Count Rate (Mcps)	0.1	1 (per pixel) 1024 (32 x 32 array)	1000	1000
Dark Counts (kcps)	200	100	16	11
Rise (ns)	0.3	0.3	2.4	1.0
Fall (ns)	0.3	0.3	6.4	1.0
Size (mm)	0.04	3.2 x 3.2	3 x 8	1.0
Temp.	-143 $^{\circ}\text{C}$	-53 $^{\circ}\text{C}$	-80 $^{\circ}\text{C}$	-20 $^{\circ}\text{C}$

InGaAs avalanche photodiodes (APDs) are widely available commercially and are routinely

used in fiber optic communications and other applications. Several authors have performed photon counting experiments with these devices [1, 6]. Commercial InGaAs APDs used in telecommunications have limited diameters (< 50 microns). Impressive performance has been achieved from a custom InGaAs APD array [2]. Unfortunately, this device is not available for purchase from the developer and independent development is prohibitively expensive. In addition, high maximum count rates and the associated photon statistics have yet to be published for this device. Both conventional and hybrid photomultiplier tubes have limited photocathode lifetimes for high-count-rate applications.

NASA laser-based remote-sensing-instrument-systems and ground-based free-space optical-communications receivers require larger area APDs than typically used in terrestrial fiber optic communications. Ground-based fieldable lidar instruments (e.g. a short range (2 km) upward looking lidar for atmospheric CO_2 [7].) require reasonably priced (< \$10k) photon counting detectors with diameters > 200 microns. Some of the detector requirements for NASA 1.0 - 2.0 μm operating wavelength lidars are given in Table II.

Table II. DETECTOR REQUIREMENTS FOR NASA
1.0 - 2.0 μm OPERATING WAVELENGTH LIDARS.

Parameter	Specification
Diameter	> 200 μm
Sensitivity	Photon Counting
Dark Counts	< 100 kcps
Detection Efficiency	> 10%
Maximum Count Rate	> 10 Mcps
Linearity	$\pm 1\%$ (DIAL only)

An orbital laser sounder [8] for generating profiles of atmospheric CO_2 is under investigation and is driving some of the detector requirements. The proposed laser sounder instrument parameters are similar to the recent ICESAT/GLAS spacecraft/instrument [9]: a 500 km low Earth orbit and a 100 meter diameter

spot on the ground (to obtain an adequate spatial average). A one meter diameter telescope with a 1.4 meter effective focal length ($f/1.4$) (with aft optics) will image the 100 meter spot on the ground to a spot size = $1.4 \text{ m} \cdot 100 \text{ m} / (500 \text{ km}) = 140 \mu\text{m}$ at the telescope focal plane. An additional consideration is maintaining the boresite alignment between the laser transmitter and the receiver telescope. If an active alignment mechanism is not employed, then additional angular margin is required to insure the laser spot projected on the ground is within the receiver field of view. An even larger detector (and/or faster optics - $f/1$) is required to allow for this angular boresite alignment margin. A detailed discussion of detector area considerations in lidar systems is given by Measures [10].

The performance of these systems is strongly impacted by the detector performance with low dark count, high-detection efficiency and large dynamic range of importance for linear mode operation. Large area APDs also provide good insight into the material quality that is required for arrays.

In this paper we summarize results from two separate efforts for the development of > 200 micron diameter photon counting InGaAs APDs. The two approaches presented are: 1) InGaAs-InAlAs and 2) InGaAs-Si devices. Fig. 1 shows comparable dark currents from three InGaAs APDs: 1) a Nova Crystals Inc. (recently acquired by Gemfire Inc.) 60 micron diameter InGaAs-Si device 2) a Spectrolab Inc. 75 micron diameter InGaAs-InAlAs device and 3) a EG&G Inc. Model 30644 50 micron diameter InGaAs-InP device (used as a baseline).

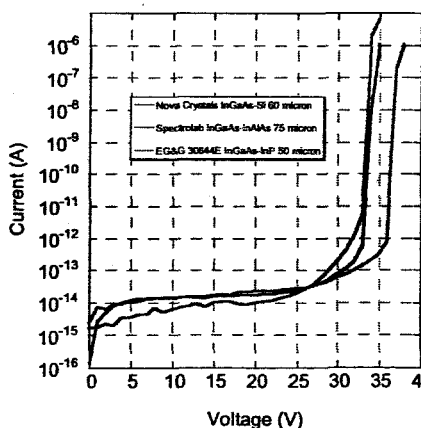


Figure 1. Dark Current vs. Voltage for InGaAs APDs as shown. Temperature = 118 K.

This indicates that the dark currents are sufficiently low for photon counting if there are no other deleterious effects.

II. InGaAs/InAlAs APDs

Spectrolab Inc. fabricated and characterized 75 μm , 200 μm and 300 μm diameter InGaAs/InAlAs APDs. InGaAs-based APDs having a spectral response between 1.0-1.7 μm . A separate absorption and charge multiplication (SACM) APD structure was grown on 2" InP n+ substrates. The structure is similar to one previously published [11]. The device layers were grown by metal-organic vapor phase epitaxy on sulphur-doped (100) InP. Trimethylindium, trimethylgallium, trimethyl-aluminum, 100% arsine, and 100% phosphine were used as source materials. Avalanche photodiodes were fabricated by wet chemical mesa etching followed by passivation. Fig. 2 is a photograph of a 200 micron diameter device.

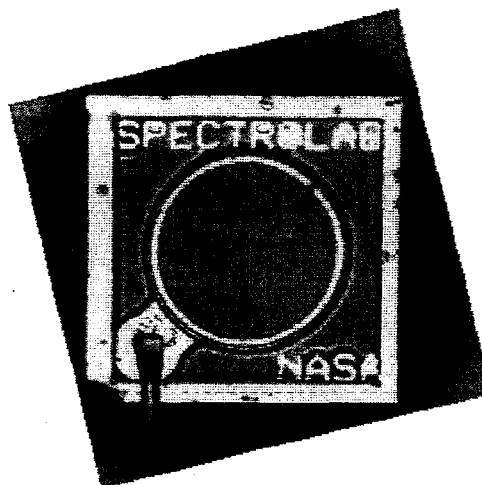


Figure 2. 200 micron diameter InGaAs/InAlAs APD.

Experimental data taken by Spectrolab Inc. [12] indicate that for this particular structure that the excess noise can be well fit using McIntyre's model [13] for noise with a k_{eff} value of 0.22. This result agrees with other noise measurements on InGaAs-InAlAs APDs [14] and points to the low noise inherent in this materials system. A low excess noise APD is critical to the efficiency of linear mode APD operation because the system efficiency will be a strong function of the discriminator threshold required to pass a voltage pulse on for amplification and counting. If the APD pulse height distribution is broad then the discriminator threshold has to be placed high

enough to reject dark counts thereby limiting the counting efficiency.

We have conducted preliminary photon counting experiments using a simple passive quenching circuit. An experiment diagram is shown in Fig. 3. All of the measurements discussed here were

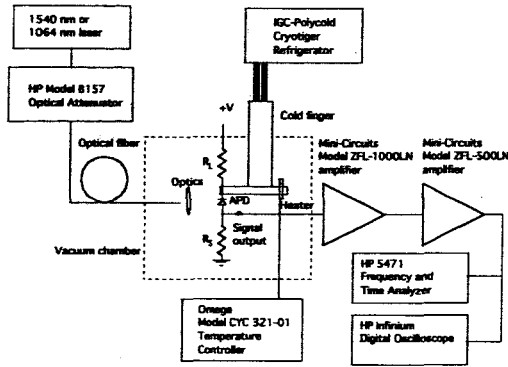


Figure 3. Photon counting with passive quenching circuit experiment diagram.

made at 1540 nm wavelength using a commercial laser diode source. We plan to also make measurements at 1064 nm in the near future. Light from the fiber pigtailed laser diode was directed through a programmable optical attenuator (HP Model 8157) and into a 200 micron core optical fiber into a vacuum chamber where it was collimated with a lens and directed to the APD. The APD was biased through a ballast resistor, R_L , and the output was coupled directly to a 50 ohm input impedance low-noise RF amplifiers (Mini-Circuits Models ZFL-500LN and ZFL-1000LN). Low temperature (120 K) operation was achieved using a cryogenic refrigerator (IGC-Polycold Cryotiger). A heater and temperature controller (Omega Model CYC 321-01) allowed for operation between 120 K and 240 K.

We measured the DC dark and light current detector characteristics using a simple biasing circuit with a Keithley Model 617 Electrometer in series with the detector. The dark current as a function of bias voltage curves for the 75, 200 and 300 micron diameter InGaAs-InAlAs APDs at 120 K temperature are shown in Fig. 4. The APDs with the lowest dark current were selected after wafer level testing. As expected, the dark current increases with increasing device area. The breakdown voltage is between 33 and 34 V at this temperature. The light and dark current as a function of bias voltage is shown in Fig. 5. The curve exhibits a knee at the punch-through voltage (~ 21 V). The punch through voltage

was independently confirmed in a separate experiment by linear mode APD gain measurements with pulse modulation on the laser. At low voltages (< 12 V), the dark current is higher than the light current. We have no explanation for this phenomenon at this time.

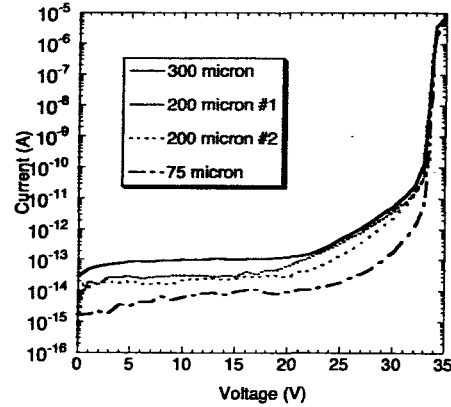


Figure 4. Dark current for various optical diameter InGaAs-InAlAs APDs as noted at 120 K.

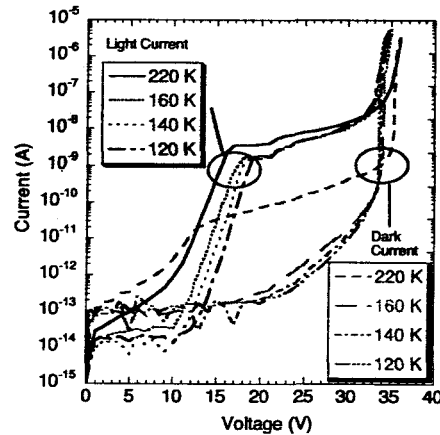


Figure 5. Light and dark current for 200 μ m diameter InGaAs-InAlAs APD at temperatures noted.

The average photon count pulse shape was recorded by an HP Infinium oscilloscope for the 75 micron diameter APD at operating at 120 K in Fig. 6, and for the 200 micron diameter APD operating at 220 K in Fig. 7. The pulse rise time (~ 2 ns) is limited by the bandwidth of our amplifier. A good discussion of the trade-offs involved in choosing the value of the ballast resistor R_L is given by Cova [15]. The quenching time constant (pulse fall time), $T_q = R_d R_L (C_d + C_s) / (R_d + R_L)$ where R_d and C_d are the APD resistance and capacitance respectively and C_s is the capacitance to ground of the diode terminal. The $R_d C_d$ time constant

of the APD remains the same with area. However, with low values of the ballast resistor, $T_q \propto 1/R_d \propto A_d$ (since all other parameters are equivalent). Since the 200 μm device has ~ 7 times larger area than the 75 micron device the quenching time constant is ~ 7 times larger for the 200 micron device.

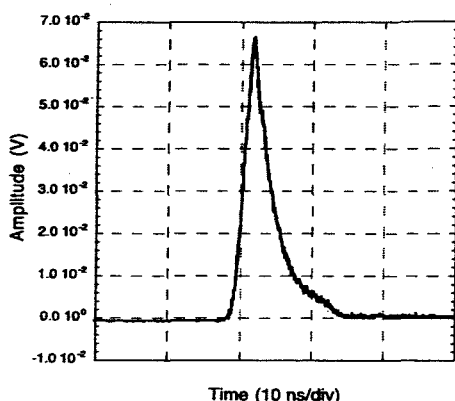


Figure 6. Photon count pulse shape (average of 32 traces) for 75 micron diameter InGaAs-InAlAs APD. The operating temperature is 120 K and the supply voltage is 33.6 V.

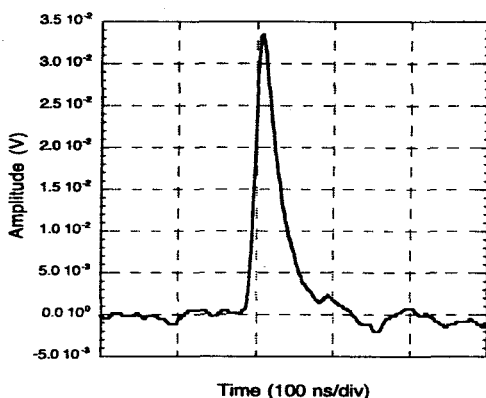


Figure 7. Photon count pulse shape (average of 32 traces) for 200 μm diameter InGaAs-InAlAs APD. The operating temperature is 220 K and the supply voltage is 35.05 V.

We experimented with several values for the ballast resistor, R_L . The bias voltage recovery time, $T_r = R_L(C_d + C_s)$ sets the maximum count rate. There is a trade-off between the achievable maximum count rate and maintaining adequate quenching. For the 200 μm APD we used a value of $R_L = 2\text{ k ohms}$. Built-in current limiting on the voltage source (Keithley Model 2410 Source Meter) allowed us to lower the value of the ballast resistor without fear of inadvertent high current damage. Both dynamic range and linearity are important for the differential absorption lidar application.

Fig. 8 shows the photon count rate as a function of optical attenuation (power) demonstrating good linearity over four orders of magnitude

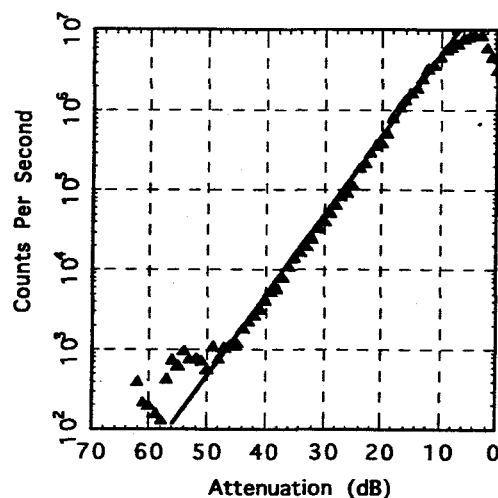


Figure 8. Dynamic Range and linearity of photon counts with 200 μm InGaAs-InAlAs APD.

dynamic range. The dark count rate for this measurement was 3.9 kcps and was subtracted off from the illuminated count rate. This is one of the most important results of this work. These data show that the photon count rate scales linearly with attenuation and demonstrates that the APD is operating as a photon counter.

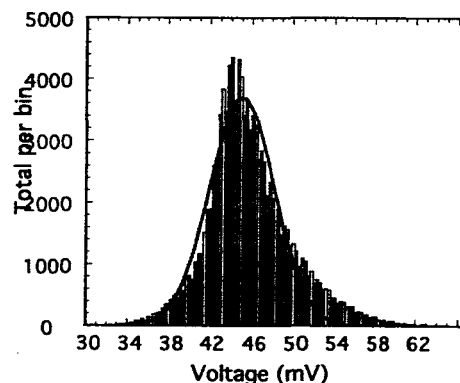


Figure 9. Photon counting pulse amplitude statistics for 75 μm diameter InGaAs-InAlAs APD follows McIntyre-Webb theory. The operating temperature is 120 K and the supply voltage is 33.9 V.

For these preliminary photon counting measurements (with a passive quenching circuit and 50 ohm input impedance RF amplifier), the counting efficiency was low ($< 0.1\%$) since the RF amplifier noise was still a dominant factor.

However, high detection-efficiency (16%) has been demonstrated on similar 160 μm diameter devices using the pseudo-active quenching (gated) circuit [16]. To reduce the circuit noise, we plan to replace the RF amplifier with a transimpedance amplifier in the passive quenching circuit. In addition, we plan to employ an active quenching circuit in the near future.

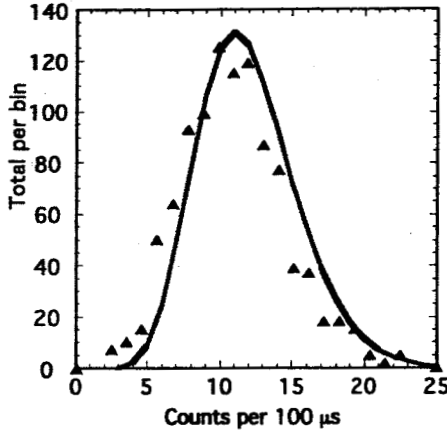


Figure 10. Photon total count statistics for a 75 μm diameter InGaAs-InAlAs APD.

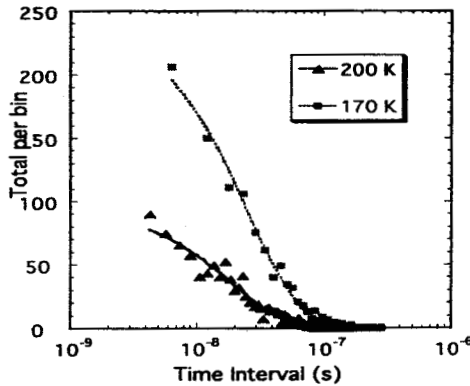


Figure 11. Photon count inter-arrival time statistics for the 75 μm diameter InGaAs-InAlAs APD at two operating temperatures.

The pulse amplitude distribution for Geiger mode APDs is given by the Webb-McIntyre-Conradi statistics [17]:

$$P(x) = \frac{1}{\sqrt{2\pi}} \frac{1}{[1 + (x/\lambda)]^{3/2}} \exp\left[-\frac{x^2}{2[1 + (x/\lambda)]}\right] \quad (1)$$

where:

$$x = \frac{m - n_e M}{\sigma}, \sigma^2 = n_e M^2 F_e, \lambda = \frac{(n_e F_e)^{1/2}}{(F_e - 1)}$$

where m is the number of secondary electrons, n_e is the number of photo-generated electrons, M is the APD gain and F_e is the excess noise factor. Fig. 9 shows good agreement between a least squares fit of this theory to the experimental pulse amplitude distribution for the 75 micron diameter APD.

The probability that n photons are absorbed from an incident optical field in a given time interval is known to follow a Poisson distribution [18]:

$$\Pr(x = n) = \frac{\lambda^n}{n!} \exp(-\lambda) \quad (2)$$

where n is the number of counts in a given time interval and λ is the mean number. Fig. 10 shows good agreement between a least squares fit of this theory to the experimental total count distribution for the 75 micron diameter APD.

The inter-arrival times of a homogeneous Poisson random point process are known to have an exponential distribution [18]. Fig. 11 shows good agreement between a least squares fit of the exponential distribution and experimental inter-arrival time data for the 75 μm diameter APD at two different temperatures 170 K and 200 K.

III. InGaAs/Si APDS

Nova Crystals Inc. in conjunction with the University of California San is producing a unique InGaAs – silicon (Si) based APD Diego [19] that promises the advantages of both detectors - high quantum efficiency in the near infrared (InGaAs) and low noise gain (silicon). They measured an ionization coefficient of 0.02 (equivalent to silicon and 10X lower than conventional InGaAs APDs) and a QE of 20% at room temperature.

Nova Crystals Inc. delivered several small diameter devices to NASA-Goddard for characterization. The dark current at low temperature (118 K) is shown in Fig. 1. Fig. 12 shows the experimental I-V characteristic of a 60 μm diameter InGaAs-Si APD at 118 K operating temperature. A hysteresis effect is observed at the breakdown voltage. A similar effect has previously been observed in Metal Resistive layer Silicon (MRS) APDs [20].

We attempted photon counting experiments using the InGaAs-Si APD in the previously described passive quenching circuit. We were not able to observe any photon counting behavior using the passive quench configuration. We attribute this to the hysteresis effect shown in Fig. 12. Nova Crystals was able to observe photon counting behavior by using pseudo-active quenching (modulated power supply) [21]. A full active quenching circuit should mitigate the effects of the hysteresis.

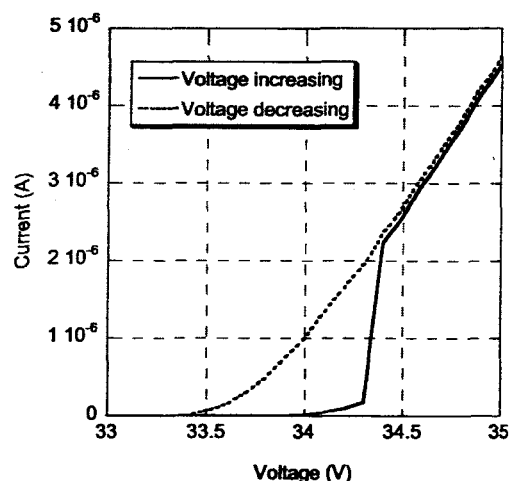


Figure 12. Hysteresis effect at breakdown voltage for 60 μm diameter InGaAs-Si APD at 118 K operating temperature.

IV. FUTURE WORK

To obtain test results in a timely manner, our experiments to date used a simple passive quench circuit. It is well known that an active quench circuit [15] is required to optimize photon counting performance. We are working with Voxel Inc. to develop an integrated InGaAs APD module that incorporates an active quench circuit. We will test prototype devices later this year.

By using resonant cavity enhancement [22], > 70% quantum efficiency has been achieved at these wavelengths at the expense of a more complex growth procedure. This would only be attempted after all other device performance goals are achieved.

Recently, the hybrid photomultiplier tube product line has received renewed interest by a number of funding agencies. A high quantum-efficiency (> 25% @ 1064 nm) has recently been achieved [23] on a new generation of improved lifetime devices. We plan to purchase and test a

device from this renewed product line specifically with lifetime issues in mind.

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